Studies for Prevention and Mitigation of Natural Disasters Using the K computer

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Japan has been hit almost every year in recent years by serious natural disasters. To prevent and mitigate the damage, it is imperative to take effective measures quickly. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) has embarked on "Strategic Programs for Innovative Research: Advanced Prediction Researches for Natural Disaster Prevention and Reduction (Field 3)," in collaboration with universities and research bodies in Japan. In the Field 3 studies, large-scale natural disaster simulations on the K computer have been conducted. We have already obtained good results such as acquiring an ability to precisely forecast Madden-Julian oscillation, obtaining high-precision tornado simulation results, carrying out advanced simulations on seismic motion, conducting high-resolution tsunami simulations related to a Nankai Trough quake, carrying out high-resolution seismic response analysis, and conducting multi-agent simulations for evacuation actions.

1. Introduction

The earthquake that struck Japan off its Pacific coast on March 11 2011 (Great East Japan Earthquake) with a magnitude of 9.0, and the giant tsunami that followed caused nearly 20 000 casualties and a huge amount of damage centered in the Tohoku region. Three years on, much reconstruction work remains to be completed. Although the Great East Japan Earthquake is a notable example, natural disasters of many types including typhoons, torrential rainfalls, and other earthquakes and tsunamis occur every year in Japan. These disasters cause considerable damage to society and the economic life of the nation, not to mention human suffering, and formulating measures to prevent and mitigate the damage is a matter of urgency in Japan. However, natural phenomena that can bring about large-scale disasters are difficult to evaluate through physical experiments, so performing numerical simulations by computer is essential to studying measures for preventing and mitigating the damage of natural disasters.

The Japan Agency for Marine-Earth Science and Technology (JAMSTEC)[1] has been at the center of government sponsored studies aimed at helping to prevent and mitigate the damage of natural disasters.[note] Using Japan's K computer and other supercomputers, these studies are conducting large-scale and high-accuracy simulations of natural phenomena in collaboration with universities and research institutions throughout Japan and are contributing to the prevention and mitigation of the damage of natural disasters. While "natural disaster" is a broad term, the research themes in the Field 3 studies can be broadly divided into "study on prediction of weather, climate and environment toward disaster prevention/mitigation" and "study for advancement of prediction accuracy on earthquake and tsunami." Important research topics are being taken up under each of these themes.

In the space available here, we present several key research results achieved using the K computer in the Field 3 studies.

note) These studies are part of "Advanced Prediction Researches for Natural Disaster Prevention and Reduction (Field 3)" (Chief Officer: Shiro Imawaki),[1,2] which are a component of the Strategic Programs for Innovative Research (SPIRE) overseen by the Ministry of Education, Culture, Sports, Science and Technology (MEXT).[2]

2. Study on prediction of weather, climate and environment toward disaster prevention/mitigation

Two key R&D topics under this research theme are "prediction of global climate and environmental changes" and "ultra-high precision meso-scale weather prediction," as described below.

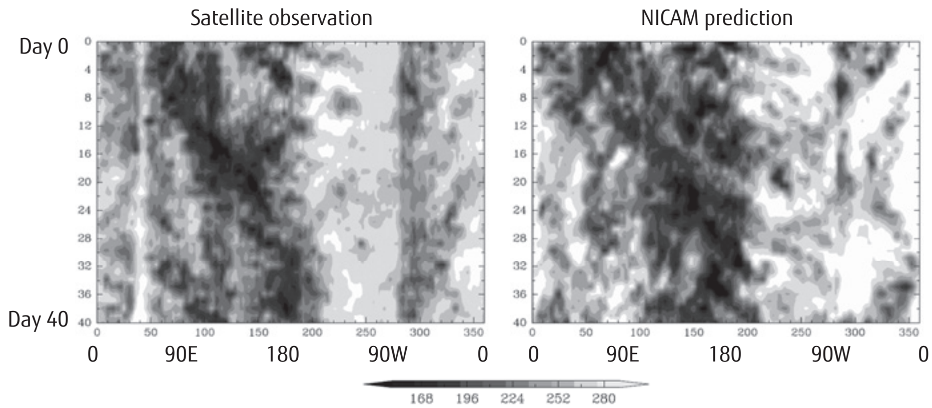
2.1 Prediction of global climate and environmental changes

This research topic, as its name implies, focuses on the climate of the entire world (global climate). Typhoons, for example, can have a major impact on Japan's society and economy, and this research aims to predict how their activity will change in an era of global warming using a high-resolution global climate model that can directly simulate cloud groups several tens of km in size.

For example, it is known that cumulonimbus clouds in the tropics sometimes form into clusters several thousand km in size and that these clusters move along the equator for a period of several weeks (**Figure 1**). It is becoming clear that this phenomenon, which consists of tropical intraseasonal changes called Madden-Julian oscillation (MJO),[3] can greatly affect the climate of various countries in the tropics and on Japan's weather as well and that it can lead to the generation of typhoons. The Non-hydrostatic Icosahedral Atmospheric Model (NICAM) developed by JAMSTEC and the Atmosphere and Ocean Research Institute, the University of Tokyo, is a global cloud-resolving model that can directly compute clusters of cumulonimbus clouds. In research to date,[4] NICAM was particularly proficient in simulating MJO phenomena, but limitations in computing resources made it difficult to quantitatively measure forecast accuracy. Up to now, only the Integrated Forecast System (IFS) model of the European Centre for Medium-Range Weather Forecasts (ECMWF) was considered to have an effective MJO forecast period in excess of three weeks. To determine NICAM's effective MJO forecast period, the K computer was used to conduct forecast experiments and associated preparatory experiments for winter MJOs over the last ten years using grids with a horizontal resolution of 7 or 14 km. Standard evaluation techniques[5),6)] showed that NICAM has an effective MJO forecast period comparable to that of the IFS model.

2.2 Ultra-high precision meso-scale weather prediction

The focus of this research topic is extraordinary weather phenomena like torrential rainfall that lead to severe damage. The accuracy of weather-related forecasts using numerical models has improved immensely in recent years thanks to advances in computer processing, but for the reasons given below, the accuracy



Horizontal and vertical axes represent longitude and time (day), respectively.
Low value (black) corresponds to cloud top.

Both satellite observation and NICAM prediction indicate that MJO convective region is propagating eastward.

Source: Tomoki Miyakawa, JAMSTEC

Figure 1
A gigantic eastward-propagating tropical storm.

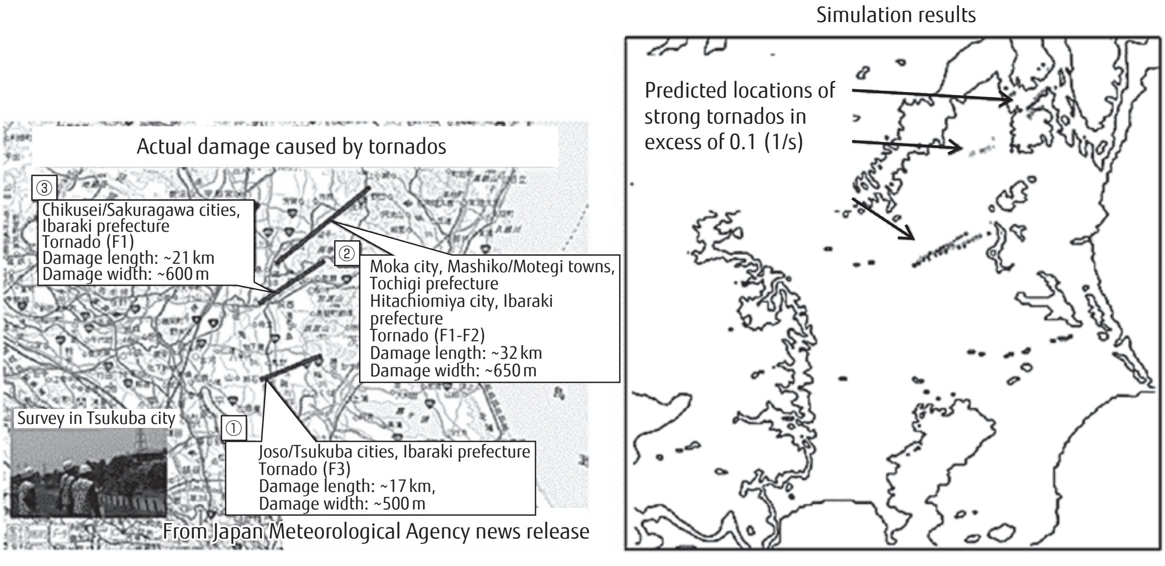
of predicting extraordinary damage-causing phenomena like torrential rainfalls and local downpours is still far from sufficient.

1) Accuracy of initial conditions in the numerical model is insufficient for the scale of the target phenomenon
2) Results are highly sensitive to slight perturbations in initial conditions and computational conditions
3) Cumulonimbus clouds cannot be directly represented with the grid spacing used in current numerical forecasts

In this research, the massive computing resources provided by the K computer were used to conduct experiments on making forecasts from many slightly different initial conditions using numerical models with fine grid spacing capable of resolving clouds. The technology developed should lead to high-precision predictions of extraordinary phenomena like torrential rainfalls and local downpours that can cause extensive damage.

Tornadoes are another type of extraordinary phenomena that can cause severe damage. The mechanism behind their generation has been studied on the basis of numerical simulations, but predicting their occurrence and movement has been very difficult. In Japan, there has been almost no research on predicting tornadoes using numerical models.

In response to this situation, a two-way nesting system was developed in collaboration with the Meteorological Research Institute using a local ensemble transform Kalman filter (LETKF), which is an advanced data assimilation technique. This system and a regional-cloud-resolving numerical model were used to "predict" the tornados that struck Tochigi and Ibaraki prefectures on May 6, 2012. **Figure 2** shows the actual locations with related information and the prediction locations of strong wind caused by the vortex of tornado obtained from multiple forecasts (ensemble forecast) in which the initial values in the model were varied slightly by using the values obtained with the LETKF.[7] The numerical model had a horizontal resolution of 350 m. Ten out of 12 computations resulted in the generation of cyclonic circulation having extremely strong vertical vorticity of 0.1 s^{-1}. These computations showed that three strong tornados passed through three locations, corresponding to the actual observations. In short, an ensemble forecast based on multiple initial conditions obtained a probability of occurrence that could not be obtained from a single forecast (deterministic forecast) and accurately predicted the locations in which strong tornados would appear. This approach will thus minimize the possibility of missing extraordinary phenomena.



Source: Hiromu Seko, Meteorological Research Institute

Figure 2
Actual damage in Ibaraki and Tochigi prefectures caused by tornados on May 6, 2012 and simulation results.

3. Study for advancement of prediction accuracy on earthquake and tsunami

The topics pursued under this research theme are broadly divided into "study on improving earthquake occurrence history," "the advancement of the accuracy of tsunami for prediction," and "natural disaster simulation for entire areas."

3.1 Study on improving earthquake occurrence history

This is a multifaceted topic that includes research on using advanced simulation of strong ground motions and tsunami simulation to predict earthquake and tsunami disasters, research on explaining slipping at plate boundaries as a cause of ocean-trench earthquakes, and research on improving the accuracy of seismic-wave movement on the earth's surface taking into account the internal structure of the earth.

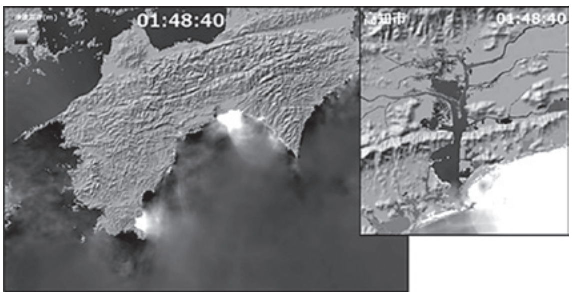
Simulation code for earthquake motion (SEISM3D)[8),9)] originally developed for the Earth Simulator at JAMSTEC was enhanced for use with the K computer, resulting in nearly perfect scaling for improved performance up to the maximum number of nodes (82 944 CPUs) on the K computer with average effective performance reaching a high level of efficiency (19.1%). This enhancement enabled earthquake motion simulation with a maximum performance of 2.1 PFLOPS, which represents a computational speed approximately 40 times greater than the maximum performance of 50 TFLOPS on the Earth Simulator using existing code.

3.2 The advancement of the accuracy of tsunami for prediction

This topic includes investigation and development of a tsunami prediction system based on tsunami databases, a tsunami propagation analysis system using real-time earthquake/tsunami data recorded by undersea water pressure meters and submarine-cable seismographs, high-accuracy tsunami simulation based on high-resolution modeling of ocean-floor topography and coastlines, and a technique for predicting tsunami damage that takes into account composite factors such as flotsam, movement of earth and sand, and fluctuation of the ocean surface.

In the high-accuracy tsunami simulation research, for example, enhancements were made to the tsunami simulation code[10)] developed jointly by United Research Services in the United States and Geoscience Australia, an Australian government institution, and spatial resolution was effectively improved through a nesting technique. The original code sequentially computes a long-wave approximation expression. The enhanced code was added the computational function for a dispersion theory and was parallelized. And the enhanced code has been optimized to run on the K computer.[11)] The latter was accomplished by improving the single-instruction multiple-data (SIMD) processing and software pipelining through loop division and by eliminating the IF statements. Additionally, data traffic and the frequency of send/receive function calls were reduced by making various changes such as upgrading the code to three-way communication suitable to the 3D logical torus-shaped network of the K computer. As a result, the performance of the main processing section of the code was doubled, and processing speed was totally increased by 7.49 times compared to the code when executing on 8748 nodes.

This new parallel tsunami simulation code was ported to the K computer. The results of test runs based on a grid model of the entire Kochi-prefecture coastline with a spatial resolution of 5 m are shown in **Figure 3**. The number of layers was set to three with the uppermost layer being the entire 1000 km × 780 km Nankai Trough area including the Kochi-prefecture coastline. This model consisted of approximately 680 000 000 cells and a time step set to 0.015 s so as to satisfy the Courant-Friedrichs-Lewy (CFL) condition and maintain numerical stability. As of November 2013, five hours



Wave heights are color-coded: white denotes 5 m or higher waves, black −2 m or lower.

Source: Toshitaka Baba, JAMSTEC

Figure 3
Wide-area, detailed tsunami simulations for Kochi prefecture.

worth of tsunami propagation simulation could be completed in just under an hour and a half when applying the above model and using 8748 nodes on the K computer. Future research includes speeding up these simulations even further.

3.3 Natural disaster simulation for entire areas

Topics covered by this research include an analysis technique for determining how an earthquake causes buildings to sway and incur damage or even collapse and an analysis technique for predicting how people will behave in an urban area struck by a disaster.

1) Analysis of earthquake effects on buildings

The E-Simulator/ADVENTURECluster software package developed by Allied Engineering Corporation and National Research Institute for Earth Science and Disaster Prevention (NIED) was ported to the K computer for performance evaluation. The performance when analyzing seismic movements using a model of a 31-story high-rise building with approximately 74 million degrees of freedom was measured, and high-speed processing could be achieved up to 512 nodes. In addition, long-period seismic movements were input into this building model, and earthquake response and elasto-plastic stress were analyzed by taking major deformation into account and using the E-Simulator/ADVENTURECluster code running on the K computer. Example results are shown in **Figure 4**.

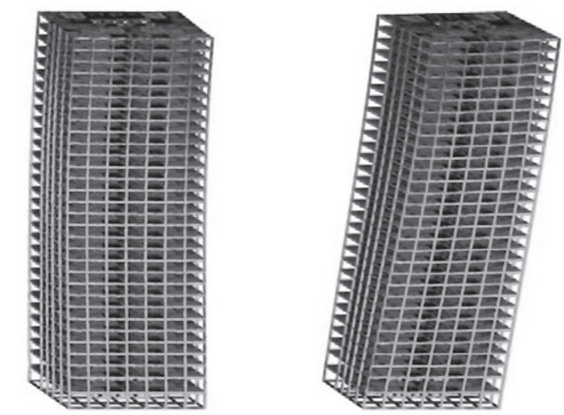


Figure 4
Results of elasto-plastic analysis for 31-story high-rise building model (deformation, equivalent stress distribution, and displacement: magnified 30 times).

2) Evacuation simulation

This research is developing a multi-agent simulation (MAS) system to simulate the movement of many people, which are represented by multiple agents. While conventional MAS packages use simple agents, the developed system uses sophisticated and smart agents that can autonomously decide their relationship with the surrounding environment and other agents and take refuge accordingly (**Figure 5**).

In addition, past research on MAS systems generally made use of a small number of targeted agents and only several tens of CPU cores; even in research handling many agents, simulations would target only about 100 000 agents using 64 cores owing to a known problem with scalability. In contrast, the current research is achieving large-scale simulations of 2 million agents through 2048-CPU highly parallel computing on the K computer using diverse techniques such as overlapping communication and computation for inter-area communications, minimizing inter-area data traffic, introducing virtual CPU topology, and applying area repartitioning.[12)]

4. Conclusion

This article introduced some of the research results achieved in the Field 3 studies using the K computer aimed at helping to prevent and mitigate the damage of natural disasters. The high-speed computing

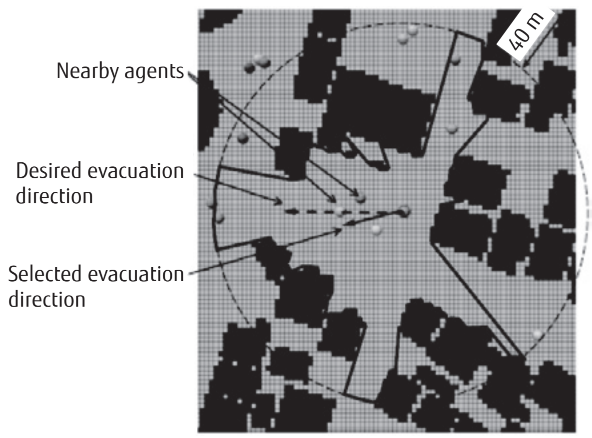


Figure 5
Identified boundary of visibility and neighbor agents (Shown in bold black line is the boundary of visibility).

performance and enormous computing resources of the K computer, in combination with the efforts of the researchers and other individuals involved, have produced research results that were heretofore difficult to achieve. Going forward, it is the desire of all those involved in the Field 3 studies to achieve even more innovative research results in the years to come.

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